BY DON ROTOLO,* N2IRZ

Digital Modulation from ASK to QAM: Alphabet Soup

Is it QPSK or 4-QAM? Or OOK? Don't worry, just ASK Don (or is that DON?). Then get out your bowl and soup spoon; we're about to serve up a byte-size portion of the alphabet soup called digital modulation (lots of letters for a bunch of ones and zeros!).

Way back in 1998, I was writing the *Digital Data Link* column for *CQ VHF* magazine, and one of the first columns I wrote explained the various digital modulation techniques in common use at the time. After 20 years, the article still holds up and remains relevant to digital communications today. So, forgive the repeat if you've see this before, but here's a (lightly updated) version of that 1998 column:

This month, we'll take a (necessarily brief) look at data modulation techniques. Although it's possible to just push bits into a transmitter, a little effort and thought can make the process much more efficient.

There are three goals in any digital modulation scheme:

1. Minimize transmitted bandwidth;
2. Minimize the Bit Error Rate (BER) for a given power level; and
3. Maximize resistance to various forms of interference.

Data communications are considered either *power-limited* or *bandwidth-limited*. Commercial services are generally bandwidth-limited: They only can get an allocation for a small slice of spectrum (often paying millions for the privilege), so they have to maximize throughput (efficiency of data transfer) with what they've got. Compared to spectrum, RF power is cheap. In the amateur service, data communications are generally power-limited: There's plenty of spectrum to play with (for free!), especially in the microwave bands, so the costs associated with greater transmit power become a significant fraction of the total system cost.

"Data communications are considered either power-limited or bandwidth-limited. Commercial services are generally bandwidth-limited ... In the amateur service, data communications are generally power-limited..."

What this means is that hams have an advantage over commercial services, namely the ability to trade power requirements for bandwidth. It should be noted that, in general, modulation schemes that use bandwidth less efficiently tend to require less power for a given BER (and the lower the BER, the higher the throughput).

Before we get into the details, I first want to acknowledge that a considerable portion of the information presented here is taken from the book *Wireless Digital Communications: Design and Theory* by Tom McDermott, N5EG. This book is published by the friendly folks at the Tucson Amateur Packet Radio Corp. (TAPR), and it's available as a free download at <https://bit.ly/2jYaEYy>. This book is jam-packed with just what the title says. I can only dream of having the level of understanding and expertise on the topic that Tom has, and I wish I could explain such complex subjects as well as he does in this book. The writing is clear, concise, and understandable, while retaining all of the sometimes difficult content so essential to comprehension. Even if you're only mildly interested in wireless data, I heartily recommend this book.

Now, let's look at some common types of data modulation.

One of the simplest modulation schemes is *Frequency Shift Keying* (FSK). Basically, you transmit on one frequency to send a binary "one," and on another frequency to send a binary "zero." It is an advantage for the frequencies to be somewhat near each other, allowing a single receiver to be used, but not so near that they interfere with each other.

The ideal distance apart can be calculated (if you want to know how, read Tom's book!). Take a look at *Figure 1*, which shows the spectrum bandwidth of a single-frequency transmitter that's turned on and off every so often. (Each FSK frequency is essentially a CW carrier switched on or off). The signal level drops off to zero at a certain distance from the carrier, then rises again to some lower level — this is a *sideband*. The distance

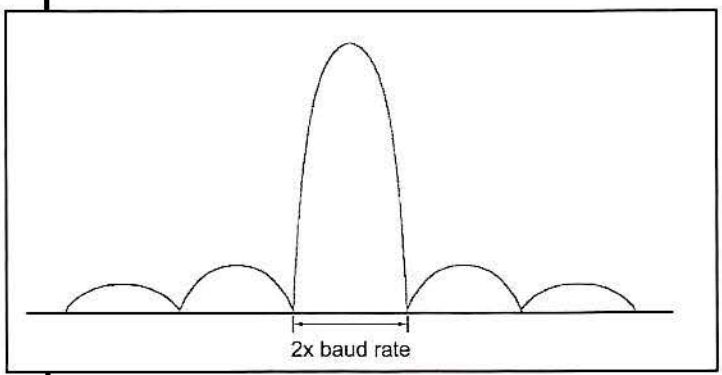

Figure 1. The spectrum bandwidth of a single-frequency transmitter that's turned on and off every so often. The bandwidth of the main carrier is equal to twice the baud rate, expressed in Hz.

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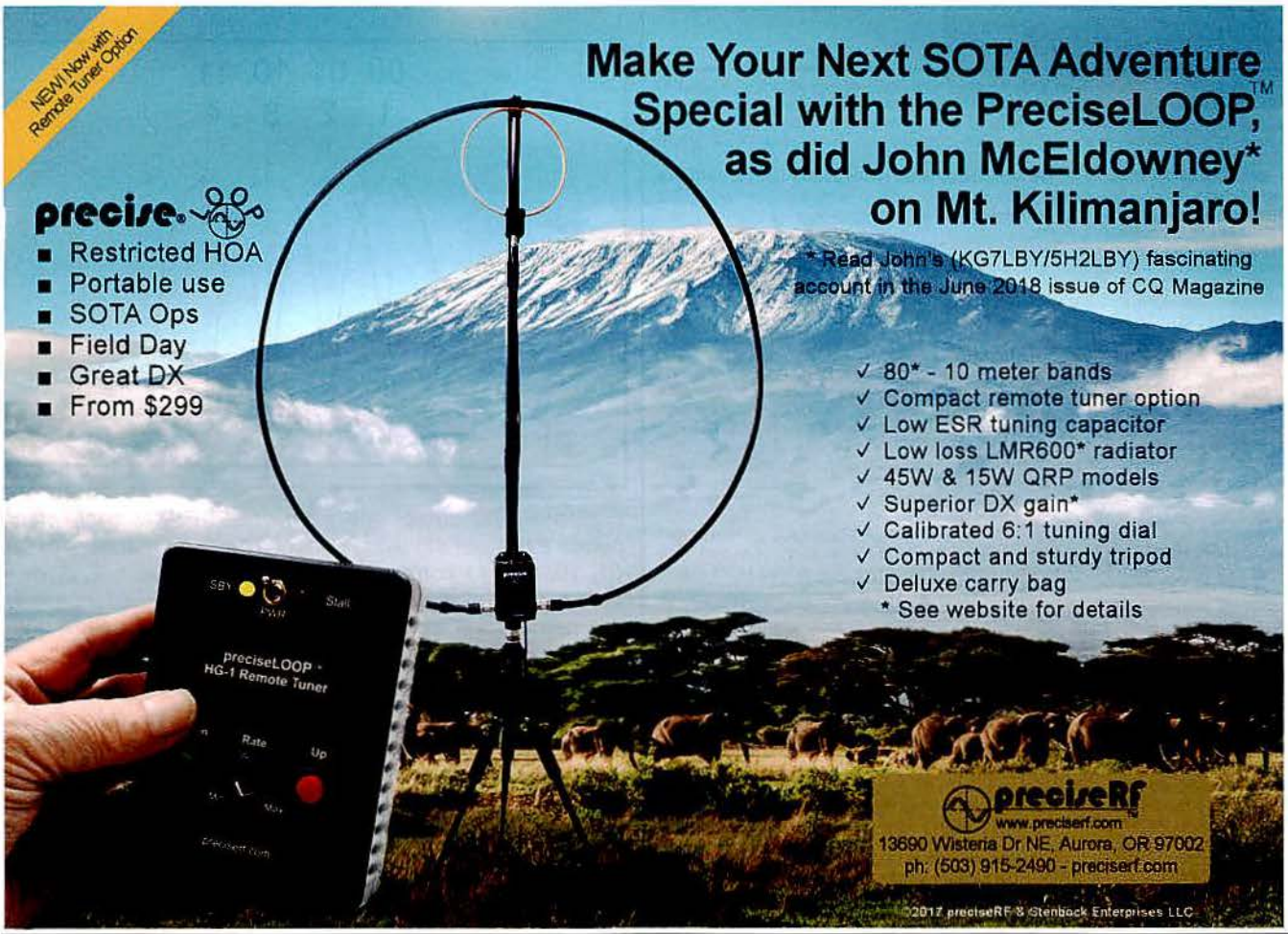
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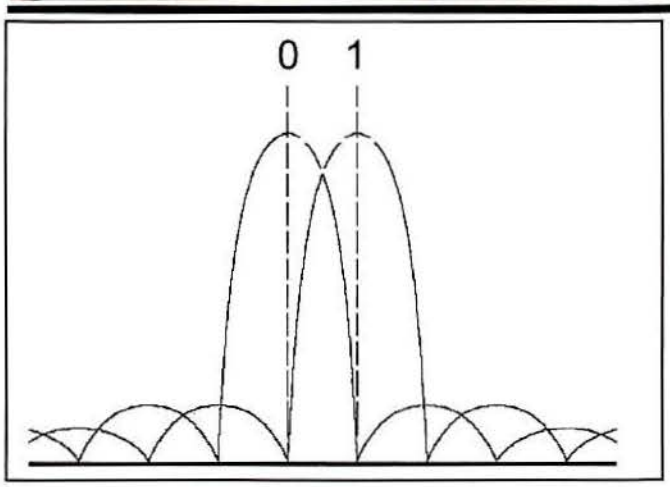

Figure 2. The spectrum of two optimally-spaced FSK carriers. Virtually no energy from the "zero" carrier is detected by the "one" receiver, and vice versa, because each signal's amplitude is always zero at the other signal's frequency.

between null points is exactly twice the baud rate, expressed in Hz (see "Bits and Bauds," elsewhere in this article).

Looking at *Figure 2*, we see that a good place for the second carrier frequency would be at the null in the first frequency's spectrum. This would make it easiest to tell one frequency from the other, making it more of an "all or nothing" decision. If the carriers were too close, we would lose some of this "all or nothing," making it necessary to have a better signal quality to ensure a given BER. We can say that this careful placement of energy, intended to minimize errors, makes the carriers *orthogonal* with each other; that is, one cannot (easily) be mistaken for the other.

Orthogonality can be accomplished at the transmitted frequency, as in this example, as well as at the baseband data level. Basically, you can use sequences of ones and zeros that are so very different, they are not (easily) mistaken.

2, 4, 6, 8

FSK using two carriers is also called 2-FSK and sends 1 bit per signaling period (*bit rate = baud rate*). To increase the number of bits sent per baud, we can use more carriers (again, see "Bits and Bauds"). *Figure 3* shows the spectrum of a 4-FSK signal, which sends 2 bits per signaling period (*baud rate = 1/2 bit rate, or bit rate = twice the baud rate*). The *di-bit* (or 2-bit-long) numbers of 00, 01, 10, and 11 correspond to carrier number 1, 2, 3, or 4 being on, with the other three being off.

This can be extended to as many carrier frequencies as you like, which actually improves performance. If we were to increase the number of carriers to infinity, the BER would become very small for a given Eb/No[1]. However, the penalty for increasing bandwidth is increased susceptibility to interference and noise.

ODFM

A similar modulation scheme is *Orthogonal Frequency Division Multiplexing*, or *OFDM* (refer back to *Figure 3*). In OFDM, instead of switching on and off each carrier one at a time, each is controlled independently, meaning that more than one signal at a time may be "on." For example, with an 8-carrier OFDM system, an entire byte (8 bits) of data is sent during each signaling period. The penalty here is that

announcements *(from page 2)*

ELYRIA, OHIO — The Northern Ohio Amateur Radio Society will hold its Annual **NOARS-FEST** from 8 a.m. to noon, Saturday, July 21 at the Lorain County Community College-John A. Spitzer Conference Center, 1005 N. Abbe Road. Contact: Tom Porter, W8KYZ, (440) 320-5523 (before 10 p.m.). Email: <noarsfest@noars.net>. Website: <www.noars.net>. Talk-in 146.70 (PL 110.9).

GERMANTOWN, OHIO — The Germantown Amateur Radio Society will hold the **GARS Germantown Hamfest** from 8 a.m. to noon, Saturday, July 21 at TriAngle Station. Contact: Phil Thomas, W8RMJ, (937) 902-6738. Email: <w8rmj@arrl.net>. Website: <http://garsohio.org>. Talk-in 443.1875 (PL 123). VE exams.

NORTH BEND, OREGON — The Coos County Radio Club will hold its **Annual Hamfest and Swapmeet** from 10 a.m. to 2 p.m., Saturday, July 21 at North Bend High School, 2323 Pacific Avenue. Contact: Joe Burkleo, WA7JAW, (541) 396-4926. Email: <joeburkleo@hotmail.com>. Talk-in 146.610- (PL 110.9) or 147.280+ (PL 146.2). VE exams.

SLIDELL, LOUISIANA — The Ozone Amateur Radio Club will hold the **Slidell EOC Hamfest 2018** from 8 a.m. to 2 p.m., Saturday, July 21 at the John Slidell Park, 105 Robert Boulevard. Contact: OARC, P.O. Box 553, Slidell, LA 70459. Email: <hamfest@w5sla.net>. Website: <www.w5sla.net>. Talk-in 147.27+ (PL 114.8). VE exams, fox hunt.

DEERFIELD, NEW YORK — The Utica Amateur Radio Club will hold **RadioCom 2018 Hamfest and Computer Fair** from 8 a.m. to noon, Sunday, July 22 at the Deerfield Firehouse Grounds, 5476 Trenton Road. Contact: Bob Decker, AA2CU, (315) 797-6614. Email: <tbd2626@yahoo.com>. Website: <www.uticaarc.com>. Talk-in 146.76-. VE exams.

VAN WERT, OHIO — The Van Wert Amateur Radio Club will hold the **30th Annual Van Wert Hamfest** beginning 8 a.m., Sunday, July 22 at the Van Wert Fairgrounds, 1055 S. Washington Street. Contact: Steve Kouts, WA8WKF, (419) 771-8152. Website: <http://w8fy.org>. Talk-in 146.850.

WASHINGTON, MISSOURI — The Zero Beaters Amateur Radio Club will hold its **56th Annual Hamfest** from 7 a.m. to 1 p.m., Sunday, July 22 at the Washington Elks Hall, 1459 West 5th Street. Contact: Bruce Serbus <kd0kcf@sbcglobal.net>. Talk-in 147.24+. VE exams.

OSHKOSH, WISCONSIN — The Fox Cities Amateur Radio Club will air special event station **W9ZL** 1400-2200 UTC daily from Monday, July 23 through Sunday, July 29 for the EAA AirVenture. Frequencies 14.250, 7.250, 50.150 on SSB. QSL to FCARC, AirVenture 2018, P.O. Box 2346, Appleton, WI 54912.

OKLAHOMA CITY, OKLAHOMA — Ham Holiday 2018 and the **2018 ARRL Oklahoma State Convention** will be held from 3-7 p.m., Friday, July 27 and 8 a.m. to 3 p.m., Saturday, July 28 at the Tower Hotel, 3233 Northwest Expressway. Contact: P.O. Box 1103, Nicoma Park, OK 73066. Email: <president@hamholiday.com>. Website: <http://hamholiday.com>. VE exams.

LANSING, MICHIGAN — The Central Michigan Amateur Radio Club will hold the **2018 Outdoor Hamfest** from 8 a.m. to 1 p.m., Saturday, July 28 at Holt Christian Church, 2424 Washington Road. Contact: Clyde Tompkins, K8CPT, (517) 489-2014. Email: <k8cpt@qsl.net>. Website: <www.centralmiarc.com>. Talk-in 145.390 (PL 100). VE exams, GOTA station.

LOUISA, KENTUCKY — The Big Sandy Amateur Radio Club will hold its **Hamfest** from 8 a.m. to 1 p.m., Saturday, July 28 at the Lawrence County Community Center, 205 Bulldog Lane. Contact: Tom Lykins, K4LID, 106 Maple Street, Louisa, KY. (606) 638-4735. Email: <k4lid@panix.com>. Website: <http://bsarc.org>. Talk-in 147.390 (PL 127.3).

PINETOP-LAKESIDE, ARIZONA — The Kachina Amateur Radio Club will hold the **White Mountain Hamfest** from 6 a.m. to 1 p.m., Saturday, July 28 at Mt. Meadow Park, 932 N. Woodland Road. Contact: Vince Cattolica, KA7JOL, (520) 591-4576. Email: <info@kachinaarc.org>. Website: <www.kachinaarc.org>. Talk-in 146.78 (PL 91.5). VE exams.

WAYNESVILLE, NORTH CAROLINA — The Western Carolina Amateur Radio Society will hold its annual **Hamfest** beginning 6 a.m., Saturday, July 28 at the Haywood County Fairgrounds, 758 Crabtree Road. Contact: WCARS, P.O. Box 1488, Asheville, NC 28802. Website: <www.wcars.org>. Talk-in 149.910- (PL 91.5) or 147.390+ (PL 94.8). VE exams.

RAVENNA, OHIO — The Portage Amateur Radio Club will hold its **Hamfair 2018** from 9 a.m. to 3 p.m., Sunday, July 29 at the Maplewood Career Center, 7075 State Route 88. Contact: Joanne Solak, KJ3O, (330) 274-8240. Email: <kj3o@arrl.net>. Talk-in 145.39-. VE exams.

AUGUST

OKLAHOMA CITY, OKLAHOMA — The Young Ladies Radio League will hold the **2018 YLRL Convention** on Thursday, August 2 through Sunday, August 5 at the Sheraton OKC, 1 North Broadway Avenue. Website: <http://ylrlconvention.org>. Email: <w5mqc@yahoo.com>.

AUSTIN, TEXAS — The Austin Summerfest 2018 and **2018 ARRL South Texas Section Convention** will be held from 6 to 9 p.m., Friday, August 3 and from 8 a.m. to 3:30 p.m., Saturday, August 4 at the Crowne Plaza, 6121 North IH-35. Website: <www.austinsummerfest.org>. Talk-in 146.94 (PL 107.2). VE exams.

CARLINVILLE, ILLINOIS — The Montgomery County Amateur Radio Club, Macoupin County Amateur Radio Club, Okaw Valley Amateur Radio Club, and Sagamon Valley Radio Club will hold the **West Central Hamfest** from 7 a.m. to 1 p.m., Saturday, August 4 at the Macoupin County Fairgrounds, 21149 IL 4. Contact: Jim Pitchford, N9LQF, (217) 248-3548. Email: <james@royell.org>. Website: <www.k9mce.org>. Talk-in 444.250 (PL 103.5). VE exams, card checking.

CENTRAL CITY, IOWA — The Cedar Valley Amateur Radio Club will hold the **First Annual Midwest STEM TechFest** and **2018 ARRL Midwest Division Convention** on Saturday, August 4 and Sunday, August 5 at the Linn County Fairgrounds, 201 Central City Road. Contact: Tim Busch, NØCKR, <n0ckr@arrl.net>. Website: <www.arrlmidwestconvention.org>. Talk-in 146.745- (PL 192.8). VE exams.

GROVE CITY, OHIO — The Voice of Aladdin Amateur Radio Club will hold the **2018 Columbus Hamfest** and **2018 ARRL Ohio Section Convention** from 8 a.m. to 1 p.m., Saturday, August 4 at the Aladdin Shrine Center, 1801 Gateway Circle. Email: <w8fez@arrl.net>. Website: <www.columbushamfest.com>. Talk-in 146.760- (PL 123). VE exams.

ONALASKA, WISCONSIN — The Riverland Amateur Radio Club will hold its **Swap Fest** from 8 a.m. to 1 p.m., Saturday, August 4 at the Onalaska Omni Center, 255 Riders Club Road. Contact: Greg Miller, K9LEC, (608) 792-7841. Email: <k9lec@arrl.net>. Website: <http://rarc.qth.com>. Talk-in 146.970 (PL 131.8). VE exams, DXCC / VUCC / WAC / WAS / 160m card checking.

TRUMANSBURG, NEW YORK — The Tompkins County Amateur Radio Association will hold the **Annual Ithaca Hamfest** from 7 a.m. to noon, Saturday, August 4 at the Trumansburg Fairgrounds, 2150 Trumansburg Road. Email: <ne2t@arrl.net>. Website: <http://tcara-ny.org>. VE exams.

PEOTONE, ILLINOIS — The Hamfesters Radio Club will hold its **84th Annual Hamfest** from 6 a.m. to 3 p.m., Sunday, August 5 at the Will County Fairgrounds, 710 S. West Street. Contact: Don Pointer, KC9EQQ, (773) 426-1936. Email: <dpointer@aol.com>. Website: <www.hamfester.org>. Talk-in 146.52. VE exams.

SHREVEPORT, LOUISIANA — The Shreveport Amateur Radio Association will hold the **Shreveport-Bossier Hamfest** from 8 a.m. to 3 p.m., Friday, August 10 and 8 a.m. to 3 p.m., Saturday, August 11 at the Louisiana State Fair Agriculture Building, 3206 Pershing Avenue. Contact: Bob Davis, N5ZVW, (318) 230-1242. Email: <hamfest@k5sar.com>. Website: <http://shreveporthamfest.k5sar.com>.

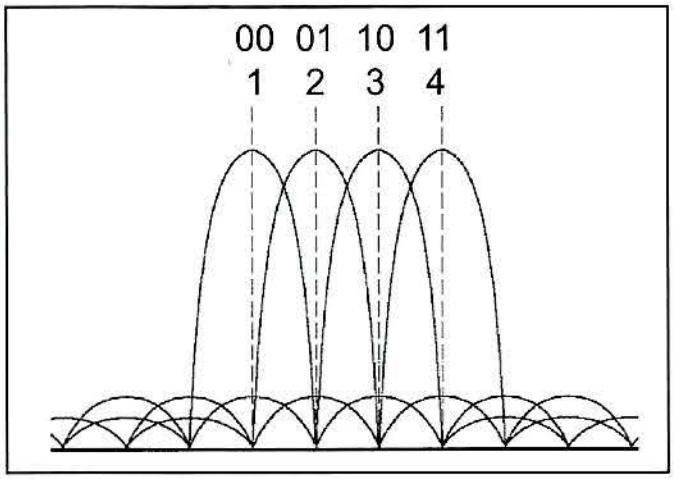

Figure 3. The output spectrum of a 4-FSK signal, which sends 2 bits per signaling period. The di-bit numbers of 00, 01, 10, and 11 correspond to carrier number 1, 2, 3, or 4 being on, with the other three being off. For OFDM (see text), the carriers are switched on and off independently, thus sending 4 bits per signaling period.

the power is equally distributed among the "on" carriers. This reduces the power of any given bit, decreasing the signal-to-noise (S/N) ratio, thus increasing the BER. Also, the variability of the signal level (the power per carrier if all 8 are on is much lower than if only one is on) causes further complications.

The PSK Family

If we can detect *phase* accurately, we can use only a single carrier frequency, changing only the carrier's phase to indicate a data bit. Phase is a *time-shifting* (usually a delay) of a periodic signal (such as a sine or square wave), expressed in degrees, where 360° equals one full *period*. Period is defined as the time from a point on one wave in a string of similar waves to the same point on the next wave. Detecting the phase of a carrier implies that we have available to us a reference signal to which we can compare the incoming signal. As it turns out, it's not difficult to regenerate such a reference carrier *from* the incoming signal.

This leads us to *Phase Shift Keying*, or *PSK*. The more accurately we can regenerate the reference carrier, the smaller the phase change we can detect. For example, even if our reference carrier swings wildly, varying by +/-70°, it is still no problem to detect a 180° phase change. If we can hold the reference to a few degrees, though, detecting a phase shift of, say, 10° isn't difficult, either. The difficulty is that holding the reference carrier so closely requires a greater Eb/No ratio for a given BER. This means having either more signal (higher power) or less noise (a quieter channel).

Figure 4 shows the possible phase angles for a *4-PSK* system, sending 2 bits of data per signaling time. The carrier phase can take any one of the four values, each representing a di-bit data number (well, not exactly, but just accept this for now). Because of the 90° phase differences, this technique is also called *Quadrature Phase Shift Keying*, or *QPSK*.

One problem with QPSK is the possibility of a 180° phase shift. This abrupt phase reversal, when passed through a Class C amplifier (typical for FM), causes a significant widening of the transmitted bandwidth. To help reduce this problem, we can limit each phase change to +90° if we *offset* one of the data streams by 1/2 bit time. *Figure 5(a)* shows a regular QPSK

di-bit data stream, and an *Offset QPSK (OQPSK)* data stream at *5(b)*.

Phase Ambiguity

One important point regarding PSK is the *absolute phase* of the reference carrier. In many cases, we can regenerate a phase-stable reference, but *we cannot always determine the constant phase offset from the transmitted carrier*. In other words, if we detect a 4-PSK signal with a 90° phase difference compared to our reference, we don't know which of the four possible phases the signal was transmitted with.

Looking again at *Figure 4*, it is completely *incorrect* to assign a di-bit number to each phase, because we can't tell which of the four phases it really is. This so-called *phase ambiguity* is resolved by only transmitting a phase change to indicate that the value of the bit has changed-from 0 to 1 or 1 to 0. So, two ones in a row wouldn't cause a phase change. You see, while we cannot determine the *absolute* phase, it's simple to see that the phase has changed, and by how much.

As I mentioned previously, the penalty for increasing the number of phases is the greater Eb/No required to hold the phase reference stable enough. For example, a certain 2-PSK system might need an Eb/No of 10 dB for a given BER, while a similar 32-PSK system would need a whopping 24 dB (nearly 25 times the signal level) for the same BER. However, for a very quiet channel (as is typical in the commercial sector), a 64-PSK system is both practical and efficient.

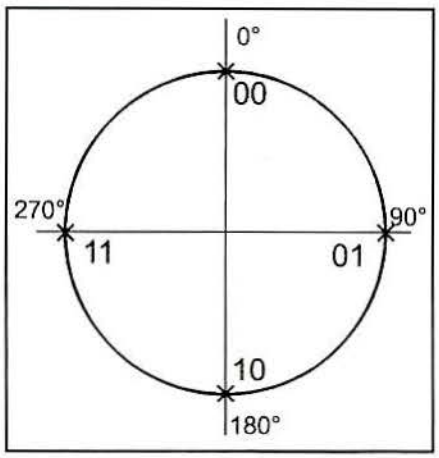

Figure 4. This phase diagram shows the four possible phase angles for a 4-PSK system. Such a system sends 2 bits of data per signaling time. Commercial modems using 64-PSK are available, but they require a very high signal-to-noise ratio for good operation. Note that, due to phase ambiguity, it's incorrect to assign a specific di-bit number to a particular phase. We did it here only to aid in explanation.

OOK, ASK, and QAM

The first digital modulation technique, used since radio began, and still in use today, is On-Off Keying (OOK). One well-known example is Morse code. This is generally unsuitable for automatic reception because it isn't orthogonal and is susceptible to noise while in the off state. Instead, we use *Amplitude Shift Keying (ASK)*, switching between a full power signal and a reduced-power (50%) signal. This helps combat interference in the off state, since fades can be detected.

It's difficult to add more levels to such a 2-ASK system, as the Eb/No requirements increase dramatically. Instead, we use a little trick: We can transmit a second 2-ASK carrier 90° out of phase from the first signal. Amplitude modulated signals that are in *quadrature* (90° out of phase) do not interfere with each other (they're orthogonal), so we effectively double the data rate within the same bandwidth. This is called *Quadrature Amplitude Modulation*, or *QAM*. In this case, we added two 2-ASK signals together in quadrature, so we end up with *4-QAM*.

Four-QAM is mathematically the same as QPSK. However, if we also vary the phase of each carrier, we can squeeze even more data in there, winding up with something like *16-QAM*, a technique considerably more efficient than 16-PSK. In fact, QAM is the predominant modulation scheme used in commercial data systems. However, this technique is not very tolerant of noisy channels.

Getting in Shape

So far, we've been only looking at data streams of rectangular bits. If we carefully shape each bit, using a sinusoid or similar shape, we sharply reduce the high frequency content of the data stream. This reduces the transmitted signal's bandwidth by reducing the amplitude of the sidebands. Although other, more rigorous, definitions exist, this is the essence of *Minimum Shift Keying*, or *MSK*.

Bits and Bauds

Although many people use the terms "bits per second" and "baud" interchangeably, they are not the same. Bits per second is fairly straightforward, but baud actually means signals per second. The important difference is that there can be more than one bit per signal! A 28.8 kilobit/sec telephone modem (old school stuff), for example, uses a baud rate of only 1200, but it sends 24 bits per baud ... and 1200 times 24 equals ... you've got it: 28,800!

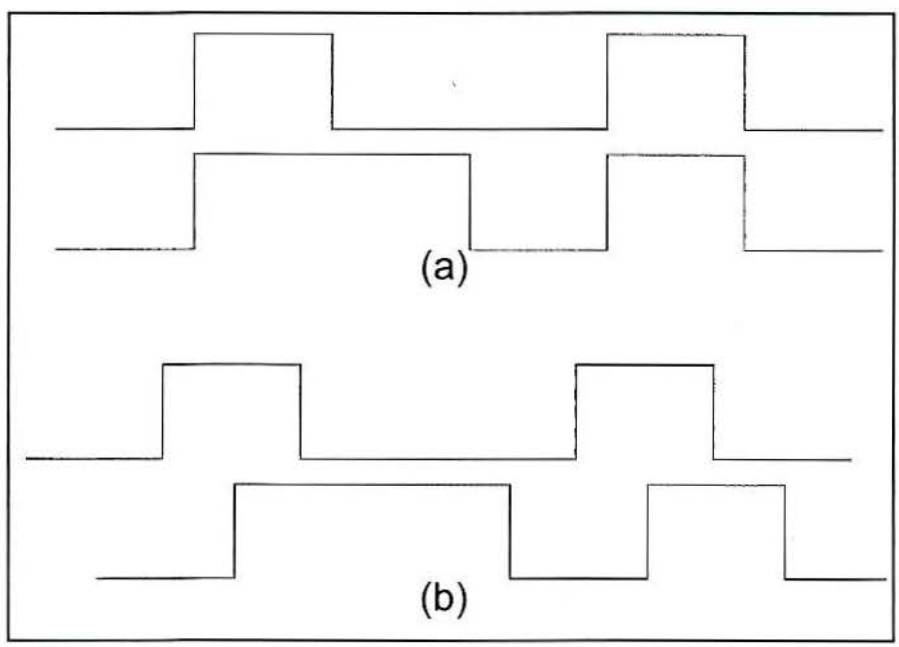

Figure 5. (a) A regular QPSK di-bit data stream without any offset between the two data streams; (b) A di-bit OQPSK data stream. Note the 1/2 bit-time offset.

Modulation Format	Applications	Advantages	Disadvantages
FM-AFSK	VHF/UHF point-to-point, multipoint	Simple, compatible with most equipment. Tolerant of frequency and deviation errors between multiple stations	Poor performance, limited speed, spectrally inefficient
FSK	VHF/UHF point-to-point, multipoint	Simple circuitry, OK for Class C amplifiers, tolerant of frequency shift errors among multiple stations	Moderate performance, wider bandwidth than other methods
PSK	Satellite, HF	Modest circuitry, excellent performance for higher data rates	Required higher signal level and linear amplification
OQPSK	VHF/UHF point-to-point	Excellent performance with optimum demodulator, OK for Class C amplifiers	More complicated circuitry, wider bandwidth than MSK
MSK	VHF/UHF point-to-point	Excellent performance with optimum demodulator, good performance with ordinary FSK detector, OK for Class C amplifiers, good spectral efficiency	Most complicated circuitry

Table 1. A summary of the advantages and disadvantages of certain modulation techniques and applications.

MSK is basically OQPSK with shaped data bits, which has the effect of making each phase transition less abrupt than the 90° jumps of OQPSK. Interestingly, the output spectrum looks just like an FSK signal with one-half the ideal carrier spacing. Thus, we can use either PSK or FSK techniques to generate the output signal. The basic technique of shaping the data pulses has advantages for most modulation techniques, but MSK is the nearly ideal case, thus the "Minimum" in the name. One well-known example of MSK techniques applied to FSK signaling is the G3RUH 9600-baud modem, commonly used for satellite work and widely available.

The last modulation system we'll look at is *Audio Frequency Shift Keying*, or AFSK, the system most commonly used by hams for packet and radio teletype (RTTY). Here, we use an audio tone to signify a 0 or 1 bit. In the standard 1200-baud modems so common in the heyday of packet radio and still in use today, these tones are 1200 and 2200 Hz. The advantage to this system is that virtually any voice-grade communications channel can carry these (or similar) tones, as they fall within the standard voice passband of 300 to 3000 Hz. This technique is also very forgiving of frequency and (for FM) modulation deviation differences between multiple stations on a channel. The disadvantage is that the data rate is somewhat limited by the choice of audio tones, as well as the equipment being used.

SPURIOUS SIGNALS
By Jason Togyer KB3CNM
spuriouscomic.blogspot.com
FAUCETS! STUFFED ANIMALS! AUTO PARTS! ... I HATE HAMFESTS WHERE PEOPLE SELL THINGS THAT HAVE NOTHING TO DO WITH RADIO!
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... I GUESS YOU DON'T AGREE.
WHAT A DEAL I GOT ON THIS!

What's the Best?

There is no ideal technique for all cases, as each one has advantages over the others in certain circumstances. A summary of the advantages and disadvantages of these modulation techniques for certain applications is shown in *Table 1*.

The main reason amateurs rarely use the modulation techniques used by commercial interests comes back to the distinction between power-limited and bandwidth-limited channels. Amateurs tend to select techniques that are technically easy to implement, while commercial systems have other priorities. There's little reason to adopt commercial techniques because, despite being more spectrally efficient, they would be more costly to implement by amateurs.

This also helps us understand why we haven't progressed much from our beginnings with 1200-baud AFSK. It is awfully simple (and cheap) to do, and 1200 baud is quite adequate for what we are doing. (It is amazing to see that statement hold true even after 20 years). There are plenty of ways to go faster — a *lot* faster — but it seems the majority of amateur work doesn't really need it (otherwise it would have been done).

I hope you enjoyed this little foray into some theory. Next time, we'll swing back to practical with a look at an inexpensive oscilloscope and how it gets used to monitor a packet radio network. *– Until then, 73 de N2IRZ.*

Note:

1. Eb = Bit Energy, No = Noise Spectral Density. Eb/No is a more accurate measure of channel conditions than the commonly used Signal-to-Noise (S/N) ratio. Shannon's Limit states that for an arbitrarily small BER, the smallest EbNo is greater than or equal to -1.6 dB.